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How do chemical substances affect the environment?

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This paper discusses problems connected with the unplanned effects upon man, his food- or resource-organisms and wildlife, of releasing naturally occurring and man-made chemical substances into the environment through human activities. The chief reason for studying this subject is the danger to human health, well-being and amenity which may be caused by unforeseen side-effects of a chemical substance during its production, transport, use and disposal. Potential harm to man is normally perceived and assessed by society on economic, social and cultural grounds. These provide the motivation for scientific research on the effects of chemical substances on the environment.

Ideally, scientists should be able to predict likely effects of a chemical directly on man or indirectly via food, crops, livestock, wildlife or climate before the substance is released, enabling a more realistic cost–benefit appraisal to be made. A first approximation to predicting a potentially harmful substance may involve the following criteria: toxic in larger amounts; biologically non-essential; accumulating in tissue with age; environmentally persistent; biochemically active; not stored in inactive deposits in tissues much faster than ingested; more harmful to certain genotypes than others of the target species; environmentally mobile in the biogeochemical cycles; not forming highly stable inert compounds in nature; increasing in the environment during the last 100 generations of the target organism.

A good deal is already known about the effects of chemical substances on man during their production, transport and use, from the study of occupational medicine, toxicology, pharmacology, etc., and to a lesser extent their effects on resource-organisms, from veterinary science and plant pathology. Much less is known about the effects of a chemical upon wildlife species, following its disposal in the environment. This last area of knowledge needs improving because ecological cycles and food chains may deliver the potentially hazardous chemical from affected wildlife back to man. Moreover, wildlife can often be used as indicators of environmental states and trends for a potentially harmful substance, giving an early warning of future risks to man.

We are also frequently ignorant of how far wildlife may be supportive to human well-being: as a food-base for an important resource-species, e.g. fisheries or grazing animals; as a key species maintaining the stability of economically valuable ecosystems; as predators of crop or livestock pests; as a species involved in mineral recycling or biodegradation; as an important amenity.

Failure to recognize the mutually interactive roles of man, resource-species, wildlife organisms and climate in the biosphere and their different tolerances to chemical substances has hindered the development of a unitary environmental management policy embracing all four biosphere components.

Although a good deal is already known about the influence of molecular structure on the toxicity to human beings of drugs and certain other chemicals, much less is known about the influence of molecular structure on the environmental persistence of a chemical. For wildlife, persistence is probably the most important criterion for predicting potential harm because there is inevitably some wild species or other which is sensitive to any compound and any persistent chemical, apparently harmless to a limited number of toxicity-test organisms, will eventually be delivered by biogeochemical cycles to a sensitive target-species in nature. This means that highly toxic, readily biodegradable substances may pose much less of an environmental problem, than a relatively harmless persistent chemical which may well damage a critical wild species.

The study of chemical effects in the environment resolves itself into a study of (*a*) the *levels* of a substance accumulating in air, water, soils (including sediments) and biota (including man), and (*b*) when the threshold action-level has been reached, *effects* produced in biota which constitute a significant adverse response (i.e. environmental dose–response curve). In order to predict trends in levels of a chemical, much more information is needed about rates of injection, flow and partitioning between air, water, soils and biota; and loss via degradation (environmental balance-sheets). These dynamic phenomena are governed by the physico-chemical properties of the molecule.

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Fluid mechanics and meteorology may in future provide the conceptual and technical tools for producing predictive models of such systems.

Most of our knowledge of *effects* derives from acute toxicology and medical studies on man, but since environmental effects are usually associated with chronic exposure, studies are being increasingly made of long-term continuous exposure to minute amounts of a chemical.

The well-known difficulty of recognizing such effects when they occur in the field is aggravated by the fact that many of the effects are non-specific and are frequently swamped by similar effects deriving from exposure to such natural phenomena as famines, droughts, cold spells, etc. Even when a genuine effect is recognized, a candidate causal agent must be found and correlated with it. This process must be followed by experimental studies, unequivocally linking chemical cause and adverse biological effect. All three stages are difficult and costly, and it is not surprising that long delays are often experienced between the recognition of a significant adverse effect and a generally agreed chemical cause. There is often ample uncertainty to allow under-reaction as well as over-reaction to potential hazards, both backed up by 'scientific' evidence.

1. INTRODUCTION

This is a very wide-ranging question, embracing several broadly overlapping aspects of chemical action upon the environment (e.g. effects of natural geo-chemical processes; corrosion of man-made structures caused by chemical agents; effects on the biosphere of chemical substances exploited by man). The ensuing discussion is confined to an appraisal of the problems encountered when dealing with the last example above. This may be stated more precisely as *the unplanned effects upon man, his food- or resource-organisms and climate, of naturally occurring and man-made chemical substances released into the environment through human activities*. Rapidly increasing chemical usage by man in the last thirty years has led to a preoccupation with possible chemical effects upon human health, the productivity of crops or livestock, and the stability of wildlife populations and climate. The chief reason for this is the danger of chemicals generating accidental or unforeseen adverse effects in the environment as outlined below in §4.

The magnitude of even this last part of the overall question precludes anything but the most generalized treatment in the following brief discussion. In one sense this may be regarded as an advantage, because the very scale of the problem tends to force scientists of different disciplines to focus detailed attention on small segments of the field in relative isolation from one another. The lack of communication which results has led to the lack of an agreed and unified conceptual approach to the study of chemical effects upon the environment. In the ensuing remarks, an attempt is made to expose some of these conceptual uncertainties. These of necessity include some of the social, economic and cultural questions upon which our motivation for the scientific study of chemical effects upon the environment is tacitly based.

2. THE NATURE OF THE PROBLEM

Chemical substances are utilized by man for many different purposes and nearly all have some disadvantages connected with the obvious benefits accruing from their use. Although it may not be too difficult to criticize several substances in this way, it must always be remembered that man consciously exploits a chemical

in the constructive belief that, on balance, it will be of real use to human society. Even the most dangerous chemicals, such as highly toxic biocides and explosives, are deliberately produced as ultimately beneficial and it is self-evident that only so long as the benefits of usage are generally agreed to outweigh the costs will a particular chemical substance remain on the market. The clear recognition of all the known benefits, costs and likely risks involved with a chemical's use and the assessment of their balance point is central to the ingenuity and skill needed to manage and control the rôles played by chemical substances in human affairs.

Comprehensive testing procedures are normally employed by industry to ensure that any man-made or naturally occurring chemical substance exploited by man has no serious disadvantages under its designated uses. If the tests prove satisfactory the chemical is released, and as a consequence the precision of the original assessment of the chemical's utility is improved with actual usage in the field. On rare occasions – e.g. with certain drugs or pesticides – harmful or inconvenient side-effects have emerged during production, usage or disposal. These were unforeseen at the time the chemical was tested and released on to the market.

In other instances, abnormally high levels of a naturally occurring chemical – e.g. compounds of certain metals (Pb, Cd, As, Hg), oxides of sulphur or nitrogen, or radionuclides – may be released by man and may accumulate locally in air, water or soil, causing effects on man and biota which were unknown at the lower concentrations occurring naturally in the environment.

Such unplanned side-effects may so alter the balance of costs and benefits that a chemical may come to be regarded as no longer appropriate for its purpose and its usage has to be restricted or it has to be withdrawn.

It is these unplanned adverse effects which are of greatest concern. They are a serious drawback when they appear after much time, money, scientific and technical resources have been spent in developing the chemical. Much would be gained if it were possible to improve our predictive capability, i.e. the forecasting of undesirable side-effects in a chemical from a knowledge of such features as physico-chemical properties, including molecular structure, biological effects upon organisms and the kinetics of movement and partitioning of the chemical throughout the media of air, water, soils and biota (environmental 'balance-sheets').

Table 1 lists ten criteria tentatively suggested here as being of primary importance when making a first approximation to determining whether a chemical may be potentially harmful in the environment. The ensuing discussion will elaborate on these criteria. It must be emphasized that such a set of general criteria will only give a very rough guide to potential hazard.

The following three areas of study emerge as pertinent to the problem:

(1) The nature of the chemical agent.

(2) The nature of the target and the kind of unplanned effects upon it.

(3) The environmental exposure régime normally required to produce such effects.

3. The nature of the chemical agent

The number of chemical substances used by man is very large and their diversity great. Although it has been estimated that some half a million chemicals are currently in use, only about 10 000 or so are produced annually in amounts between 500 and 1 000 000 kg. Their nature is so varied that they are usually classified into broad usage classes: biocides (e.g. bactericide, fungicide, insecticide, rodenticide); cosmetics; drugs; food additives and preservatives; minerals; domestic or industrial chemicals (e.g. surfactant, bleach, plastic, catalyst, metal, pigment, dyestuff); waste by-products.

TABLE 1. CRITERIA SUGGESTED FOR A POTENTIALLY HARMFUL CHEMICAL

(1) toxic in larger amounts (acceptable daily intake $< ca.$ 100 mg/kg body mass)

(2) non-essential for life-processes (N.B. all active allochemicals)

(3) accumulates with age (i.e. incompletely excreted, or detoxified)

(4) environmentally persistent (poorly biodegradable; thermo-stable in air below 200 °C)

(5) biochemically active (e.g. modifying: enzyme activity; protein synthesis, redox states)

(6) rate of sequestration (deposition in fat or bone, etc.) similar to absorption rate (i.e. pool of active chemical in tissues and body fluids)

(7) wide variation in toxicity with age or genotype or nutritional state (i.e. susceptible groups within population)

(8) environmentally mobile (i.e. relatively low boiling-point or melting-point; relatively high vapour pressure at s.t.p.)

(9) does not form relatively stable (inert) complexes with organic matter, clay-colloids, sediments, acid soils

(10) pronounced increase in human environment in last 2000 to 3000 years or in environment of target species during its last 100 generations

Many of these chemicals may be regarded as quite passive in the environment (e.g. common rocks, certain plastics) because they are sufficiently unreactive or insoluble to have no discernible chemical effect upon man or the organisms which support human life. On the other hand, there are many active substances soluble and reactive enough to influence the chemical processes which sustain life either by direct action or after they have been altered by some naturally occurring molecular transformation following their appearance in air, water, soil, or living tissues. (See table 1, criteria 1 and 5.)

Many of the chemicals in use by man have always occurred naturally in the environment of the pre-industrial globe (i.e. protochemicals – salts, sulphides and oxides of the chemical elements, radionuclides, carbohydrates, fats, proteins, alkaloids), whereas others appeared in the biosphere for the first time when they were synthesized by man (i.e. allochemicals – certain halogenated hydrocarbon

pesticides, some dyestuffs and other complex organic or metallo-organic compounds).

The significance of this distinction is that genetic selection and other evolutionary processes have operated throughout the history of every living species to minimize the harmful effects of any potentially toxic protochemical. Thus, all such substances, at the exposure levels normally occurring in nature, are either poorly absorbed, rapidly excreted or rendered inactive (by breakdown, deposition in storage depots, etc.). Improvement and geographical spread of these existing autoregulatory mechanisms by natural selection might be expected to equip organisms to survive man-made excesses of protochemicals (e.g. heavy-metal tolerance in grass species), whereas, by contrast, no such homoeostatic processes can automatically be expected to exist for allochemicals (table 1, criteria 2, 3 and 10). The time scale for such selective processes is generally considered to be several times the generation time for the organism concerned, and much longer for the evolution of tolerance to an allochemical. Both may be drastic processes leading to the death of sensitive individuals and the ultimate appearance and/or survival of tolerant genotypes (e.g. DDT tolerance in laboratory mice (Ozburn & Morrison 1964) and in several insects – bed-bug, mosquito). The severity of the process is dictated by the toxicity and prevailing concentrations of the chemical concerned and the inherent genetic variability of the affected species (criteria 1 and 7). The resulting perturbations in population size persist in relation to the generation time of the species involved (criterion 10). Although this process may be part of the micro-evolution of a species, for man it is ethically unacceptable.

4. TARGETS AND EFFECTS

(a) General considerations

Potential nuisances to man arise from the nature of the target and the type of harmful effect produced on it by chemicals as follows:

(i) Chemical effects on man himself from ingesting contaminated air, water, food, or directly from drugs or contact, causing human health problems.

(ii) Chemical effects on livestock, crops or other cultivated species and resource organisms (e.g. forest trees, fibre plants). Absorption from contaminated air, water, soil, food, or from direct chemical treatment, may cause reduced productivity of the resource species.

(iii) Chemical effects on wildlife which maintain the physical, chemical or biological stability of the environment or which influence the productivity of human food organisms. Absorption from contaminated air, water, soil, or direct chemical treatment may cause reduced productivity, reduced genetic variability or species loss (e.g. in marine organisms forming the food-base of a commercial fishery; in natural predators of crop-pests or disease vectors; in decomposer organisms involved in recycling minerals; in a key wild species responsible for maintaining the stability of an ecosystem useful to man).

(iv) Chemical contamination of the atmosphere and lower stratosphere by trace gases (e.g. CO_2, H_2O) and aerosols, which might affect global radiation balance and hence climate, causing sea-level changes, vegetation changes, etc.

It is important to recognize that these four categories are not isolated from one another but are mutually interactive components linked by the atmospheric, hydrological, geochemical and ecological processes which control the movements, distribution and effects of chemical substances injected into the biosphere. In this way, a chemical substance disposed of by release into air (chimney emissions) or water (sewage wastes) or soil (dumping) can become redistributed among all three media. The contaminant is then available for absorption by a resource species either directly or via wildlife species which may act as a food base. Climatic changes could affect the productivity of a wild or resource species. In all cases, the ultimate recipient is man.

The four divisions above are listed in the most likely order of their probable risk to man. But there are grounds for believing that item (iii) — wild species — followed by item (iv) — climate — may at present constitute the greatest areas of uncertainty in our knowledge. This is because a long-standing study of human and veterinary medicine, pharmacy, toxicology and crop pathology has thrown much light on the potential dangers and risks to human health and the productivity of cultivated species. By contrast, the environmental study of wild species has only just begun and until very recently was largely preoccupied with elucidating the extreme complexity of species assemblages found in nature. The world's half a million species of plant life and the one and a half million or so known animal species presents a bewildering variety of biological material whose reactions and degree of resistance to chemical substances vary widely from species to species. By comparison, understanding the situation for man as a single species or for the hundred or so important cultivated species is relatively simple.

(b) The significance of wild species

The significance of wild species needs further discussion because scientists differ widely in their attitudes to the importance of wildlife when assessing potentially adverse chemical effects on man. At one extreme, many biologists, agricultural and medical authorities would consider chemical contamination of wildlife as having no practical relevance whatever to human health and well-being, regarding the loss of wild species-populations as at most the loss of a pleasant amenity. At the other extreme, many biologists, ecologists, geochemists and oceanographers would regard all the components of the biosphere, including man, as so closely integrated into a system tending to equilibrium that any perturbation in a wild-species population caused by a chemical substance would be seen as a symptom of irreversibly disruptive change inimical to human survival. Scientists who have been traditionally employed in environmental management for human health and agriculture may tend to take the former outlook, while

those who have studied the environment as a contribution to pure science may tend to take the latter view. National attitudes may also differ. Countries with a long history of environmental modification for agriculture and industry may tend to the former view, whereas developed countries with a landscape which is either largely unmodified or not publicly recognized as being so may tend to the latter view.

A middle view accepts the closely interlocking nature of relationships between all biota including man, but believes that any perturbation in a wild-species population always tends to equilibration rather than disruption through the operation of homoeostatic mechanisms, and further, that there is sufficient inertia and/orilit flexiby in any ecosystem to absorb quite severe perturbations before irreversible breakdown is reached. The evidence usually adduced for this is the large number of rather stable agricultural and other man-made ecosystems throughout the world which, although differing drastically from the original wild ones they replaced, are still quite viable even if considerably simplified alternatives.

The examples given under item (iii) in §4(a) above are fairly typical of cases where wild species are supportive of human welfare; the benefits they confer upon man may even be quantifiable in monetary terms. In addition to such examples, there are cases where the affected species is of high amenity or leisure value or of cultural significance to man. Plant species for landscaping, game-species, sport-fish, 'nature-trail' species and even species figuring on national emblems all have their undoubted significance to modern life, but their value to the health and well-being of a nation cannot as yet be expressed financially.

A more widely agreed useful role for wild species is the part they may play as indicators of chemical states and trends in the environment. A chemical contaminant may be building up locally in the environment so as to pose a future hazard under one of the above divisions in §4(a) above. An early warning may be obtained from wild species either by examining the levels of a chemical substance accumulating in their tissues or by recognizing the appearance of toxic effects in the species, rather like the miner uses the canary as an indicator of bad air in the mine.

Ideally, indicator organisms should: (i) indicate that the uncontaminated environmental state (baseline) no longer exists (index of qualitative change); (ii) indicate how far contamination has advanced towards the point of significant adverse response. The rate of advance can be obtained from time series of observations (monitoring) so that avoiding action can be taken in good time if necessary (index of quantitative change). As classified by Jenkins (1971), they can fulfil the following functions:

(i) Dying in polluted situations (stochastic response to rising pollution levels): introduced 'sentinel' species, e.g. mine canary for harmful gas; tobacco for total atmospheric oxidants and *Gladiolus* for atmospheric fluoride. Naturally occurring 'detector' species such as lichens and mosses show interspecific tolerance differences to atmospheric sulphur dioxide and fluoride levels.

(ii) Thriving in polluted situations only – 'indicators'; e.g. coliform bacteria as indicators of faecal pollution of water.

(iii) Reacting physiologically or chemically to toxic contaminants in a standard reproducible way. 'Bioassay' species are usually exposed under controlled conditions, e.g. nylon-mesh bags containing *Sphagnum* or *Hypnum* collect airborne metals (Goodman & Roberts 1971) or 'accumulator' species accumulate large quantities of a contaminant when living freely in the polluted environment, e.g. pike accumulating mercury (Johnels *et al.* 1967).

Because they react toxicologically to contamination levels, indicator organisms translate chemical dosage situations into biological response terms and may thus be a convenient substitute for man as a target organism.

The early warning capability provided by tissue analysis can also apply to levels of chemical substances accumulating in air, water and soils. A knowledge of the dosage–response curve for a particular chemical substance when acting upon man, sometimes obtained from occupational exposure data, can be calibrated against levels accumulating in similarly exposed air, water, soil and biota. In this way it is possible to derive working limits and agreed standards for levels of a chemical in the environment which are acceptable to man. Subsequent environmental monitoring of air, water, soils and biota can then help predict any possible future hazard for man *before* he is affected.

Thus, the natural environment can be of value to man as a resource in its own right as a cultural amenity or as a useful indicator of future potential hazard to human beings.

Many of these considerations are as yet only at the conceptual stage. We frequently do not know which wild species act as the food base for a resource species. Natural predators of the pests of resource species often remain unknown and the functional rôles of wild species in important ecosystems are usually unrecognized. This means that as yet we are often unable to distinguish ecologically important wild species which should be conserved from less ecologically significant species which are rather more expendable. We are also a long way from a comprehensive list of usable indicator species (but see I.B.P. 1972).

To many, the man-induced attenuation of a so-called 'expendable' species, even of a pest-organism, is an act of vandalism far more serious than the wilful destruction of great art treasures. There is a finality about the extermination of even a quite 'useless' species which sows doubts in the most utilitarian mind and lays the present inhabitants of the globe open to the charge of environmental fecklessness from future generations. Although such problems are concerned with value judgements and are clearly cultural, not scientific, the whole approach of environmental science and technology is conditioned by prevailing social attitudes to them.

5. TYPES OF EXPOSURE

The interrelated nature of the four divisions (§4(*a*) above) can also be seen by examining the exposure régime to which the environment is subjected (table 2). Any given chemical will affect man, resource-species, wild-species and climate during the various phases of its production, transportation, use and disposal. Man himself can be influenced during all four phases whereas resource species, and more particularly wild species, or climate are usually influenced during the disposal phase. Cultivated species and any associated wild species can also be affected during the use phase if the chemical is an agro-chemical.

TABLE 2. SUMMARY OF CHEMICAL USAGE BY MAN

(1) produce chemical	biocide; cosmetic; domestic or industrial chemical (e.g. *catalyst, metal, pigment, radionuclide, surfactant*); drug; food-additive; mineral; waste by-product	(1) occupational exposure
(2) transport chemical	inside or outside works (road, rail, sea)	(2) accidental exposure
(3) use chemical	in agriculture; food-processing; home; industry; medicine	(3) usage exposure
(4) dispose of used chemical or waste by-product	domestic and industrial effluents to rivers and seas; aerial emissions; dumping on land and at sea	(4) ecological exposure
(5) results of disposal	(A) dispersal by *dilution* in biosphere; biogeochemical cycles redistribute chemical in media of air; water; soils; biota (including man) to give: (i) loss from some media–air, water (ii) accumulation in other media – soils, sediments, some biota, often in a stable or sequestered form (B) destruction by *molecular transformations* (i) microbiological oxidation, burning (ii) biodegradation – micro-organisms in soil, water, 'sewage' works (iii) detoxification – biochemical degradation within higher organisms	

Considerable attention is often given to spectacular accidental spillages of chemicals during transportation, e.g. the 'Torrey Canyon' oil-tanker which sank off the Cornish coast in 1967, releasing 90 000 tonnes of crude oil. They are very dramatic and stimulate public awareness and government concern, but are almost always far less serious than the cryptic but far more widespread effects of low dosages of a chemical liberated over a long period of time as is the case with ecological exposure following disposal (Baker 1971).

Traditionally, the forms of exposure stemming from production, transport and

usage have been the concern of occupational medicine, toxicology, pharmacy, etc. There is no equivalent science dealing specifically with the particular problems of ecological exposure following disposal, which emerges as the least understood of the four exposure phases in table 2.

6. Levels and effects

From the foregoing discussion it may be seen that our greatest lack of knowledge is connected with (a) the fate of a chemical substance in the biosphere as its levels build up following its disposal and (b) what effects such prevailing levels will produce upon wild species. Moreover, we lack an accurate assessment of the importance of wild species as supportive to human health and well-being.

Since our knowledge is most limited in these respects, it is perhaps not surprising that some of the best examples af unplanned side-effects appear in such situations. Table 3 lists some levels in the environment and effects on biota of one of the most intensively studied active allochemicals, p,p'-DDT and its natural metabolites DDE and DDD (ΣDDT). On some occasions the DDT is a residue left in crops, etc., after it has been applied to them as a pesticide treatment. However, most of

TABLE 3. RANGE OF LEVELS AND EFFECTS OF ΣDDT† IN THE BIOSPHERE
(EXPRESSED AS ng/g FRESH MATERIAL TO THE NEAREST FACTOR OF 10)

0.01	in sea water, blocked development of certain calanoid copepods
0.1	in rain falling over the U.K. and certain oceans
1	untreated soils in remote areas
1	solubility of p,p'-DDT in water
1	in water, may kill some trout in 100 days
1	average daily intake/g body mass, from U.K. human diet
10	W.H.O./F.A.O. proposed acceptable daily intake for man/g body mass
10	fresh cow's milk in the U.K.
100	in fat of Weddal seal and penguins, Antarctica
100	in fresh human milk (U.K. and U.S.A.)
1 000	in human fat (U.K.)
1 000	in U.S. lake trout fry, high mortality at late yolk-sac stage
10 000	in human fat (U.S.A.)
10 000	in fatty tissues of grey seal (S.W. England) and common seal (E and NW Scotland)
10 000– 100 000	experimentally lethal concentration in brains of many birds and mammal species
100 000	in diet, experimentally induced significant eggshell thinning in mallard but not in coturnix quail
1 000 000	in fat of healthy herring-gull,‡ slightly impaired reproduction
1 000 000	in fat of healthy adult pheasants‡ with chick survival 90 % of normal
1 000 000	in fat of healthy U.S. workers formulating DDT for $ca.$ 20 years
10 000 000	in pectoral muscle of white-tailed eagles found dead (Stockholm Archipelago)

NOTES: 1. Data abstracted from numerous scientific papers in current literature.
2. All organisms were alive and apparently healthy and unaffected unless otherwise stated.

† ΣDDT = DDT + DDE + DDD.
‡ Some mortality in adult population.

the levels are as a result of DDT accumulation in various media and biota to which it was not originally applied, but which it has reached from another source by the normal processes of atmospheric and biogeochemical transport. Such results were unplanned and unforeseen at the outset and are sometimes inconvenient for man. (See also Gunn 1972.)

The range of Σ DDT concentrations from table 3 spans nine orders of magnitude and significant adverse effects on biota can be seen across the range. Aquatic wildlife- or resource-species appear to be the most sensitive, with man apparently least affected (but see Radomski, Deichmann & Clizer 1968) and terrestrial mammals and birds somewhere in between. Effects on wildlife species appear to occur across the whole range. Different groups of scientific specialists concerned solely with human health or with resource-species or with aquatic or avian organisms have sometimes assumed that the safety levels peculiar to their own interests apply universally. In the past this may have led to some medical authorities being dismissive or complacent about potential risks to biota and to some biologists being alarmist about potential risks to man. This has frequently confused attempts to make a rational appraisal of costs and benefits in the use of DDT and similarly for several other chemicals (e.g. certain other organochlorine pesticides; mercury and other potentially toxic heavy metals; cyclamates; certain herbicides; and sulphur dioxide). Until this rather elementary fact of interspecific differences in tolerance to a chemical substance is clearly appreciated along with the mutually interactive relationships which exist between man, other biota and air, water and soils, these problems will continue. The diffculty is really one of inadequate flow of information and understanding between the various compartmentalized sectors of science, technology and executive control upon which a unified environmental management policy depends. Several countries are finding that 'learning by their mistakes' is a rather costly way of re-education in this sphere and have restructured their management approach.

Central to the purely scientific aspects of the problem is a more accurate and widespread knowledge of levels and effects of chemical substances released to the biosphere.

(a) Levels

A better understanding of levels of a chemical substance prevailing in the biosphere presupposes a better knowledge of the kinetics of its transport, dilution and flow-rates in the environment and the mechanisms which control these. There are three principal directions of variation which interact to produce existing levels of a chemical substance in air, water, soils and biota: (i) spatial spread; (ii) persistence of the molecules unchanged by biological or chemical degradation; (iii) rate of exchange at the interfaces between air, water, soils and biota.

Environmental transport mechanisms may operate, spreading the chemical laterally to give local, regional or global distribution patterns in the media and their associated biota. Likewise, vertical spread to the stratosphere, troposphere,

soils, upper (mixed) oceanic layer, deep oceans, or sediments can occur. The scale of spread depends upon the form of the emission – solid, liquid or gaseous – and upon the physicochemical characteristics of the substance. For instance, the size of the transported particles, vapour pressure, melting-point, boiling-point, redox potential, pH, water- and fat-solubility, affinity for proteins and soil colloids will determine such characteristics as whether the substance will co-distil with water to become widely distributed, or fix in body fat, protein or soil colloids to become more or less stably bound in biota, soils and sediments. Dimethyl mercury, boiling at 96 °C, participates in the hydrological cycle, as does DDT by virtue of its high vapour pressure and co-distillation properties. Potentially toxic non-ferrous metals can be firmly bound on to the phenolic and carboxylic groups of clay minerals and organic matter in the surface layers of soils. Monomethyl mercury and DDT may be more or less stably fixed in the protein and fatty tissues respectively of biota (see table 1, criteria 8 and 9). Much has been written about the process of accumulation by which a non-degradable poorly excreted chemical substance may become magnified as it passes through the food-web. Successive trophic levels from primary producer (plant-life) to herbivores, to carnivores, concentrate the substance and enrichment factors of 100 000 have been commonly reported for several non-ferrous metals, e.g. Cd, Hg, and for organochlorines.
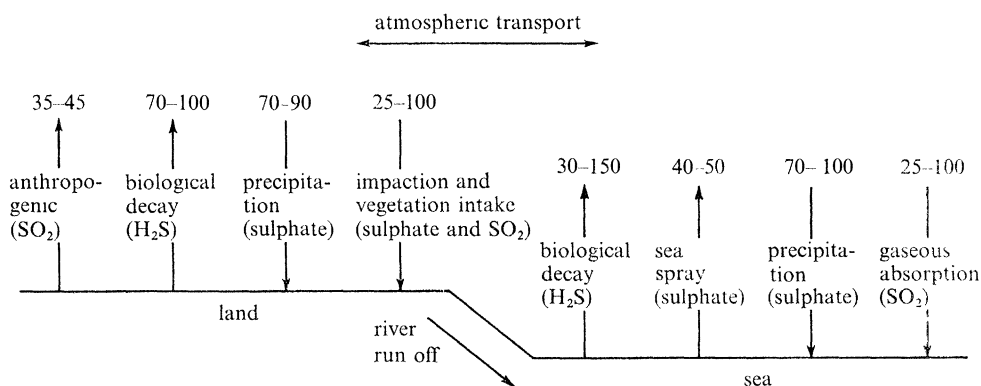

FIGURE 1. Global 'balance-sheet', showing principal sources and sinks for sulphur, around the year 1965 (expressed in millions of tonnes S/annum). Taken from Swedish Preparatory Committee Report (1971).

Such properties will also determine the interface partitioning of a substance between air, water, soils, and biota, while its chemical properties will determine its chemical or biological degradability (table 1, criterion 4). Spread, degradability and exchange-rate will co-act to determine the mean residence time of a substance in any medium and persistence in the scale of minutes, days, years and centuries are all common (e.g. SO_2, alkoxy-alkyl mercury, DDT, ^{239}Pu respectively).

At present, far too little is known about steady-state and transient patterns of flow-transport, partition and accumulation peculiar to the more important sub-

stances. Although the fluid mechanics of certain atmospheric and water-borne contaminants have been studied to elucidate spatial distribution patterns (figures 1 to 3) we have little data on mean residence times of contaminant chemicals in the various media. Engineering and meteorological techniques are, however, available to produce crude explanatory models which could be successively refined to create predictive models capable of forecasting future distribution pictures for important chemicals.
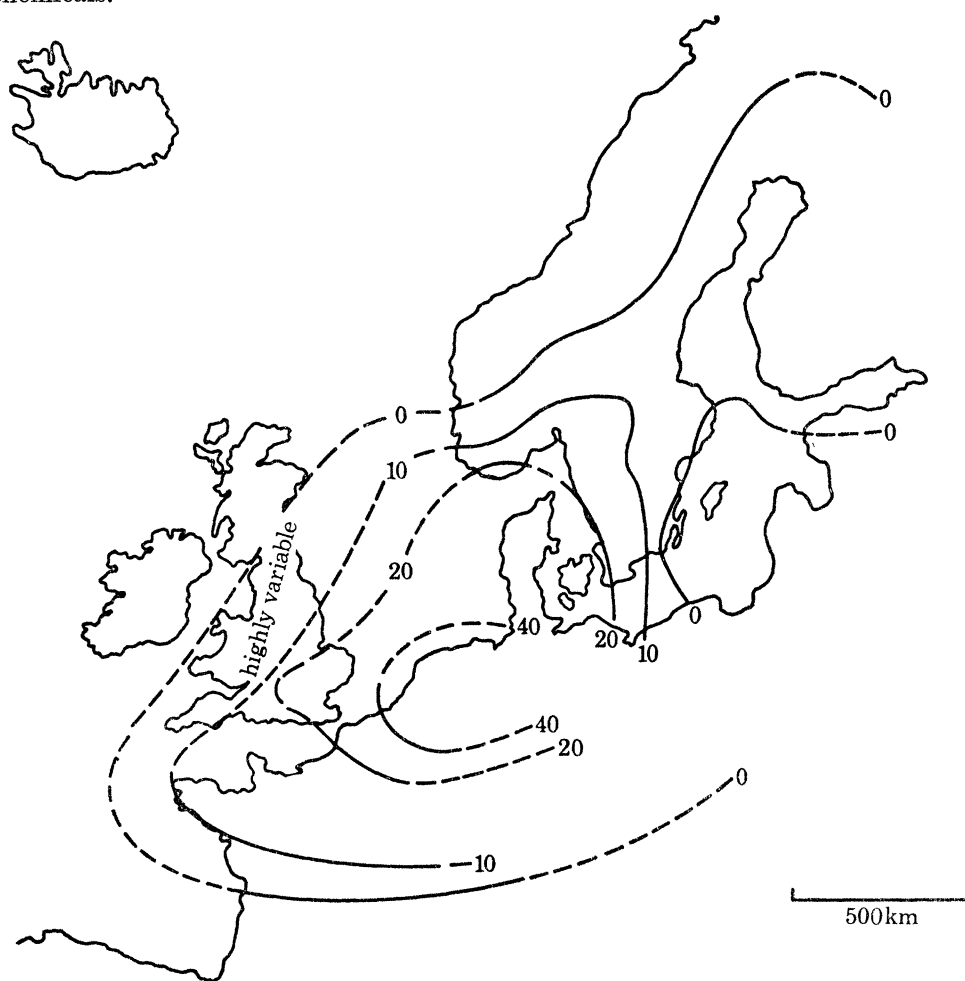
FIGURE 2. Regional deposition of excess acid via precipitation around the year 1965 (expressed as mg $H^+ m^{-2}$ per annum). Taken from Swedish Preparatory Committee Report (1971).

(b) Effects

Table 4 summarizes the way in which the level of a substance (recognized by chemical analysis) can rise from its normal 'natural' or 'background' concentrations to a point where it has sufficient reaction upon man or biota or climate to produce a significant adverse effect (recognized by toxicological or medical
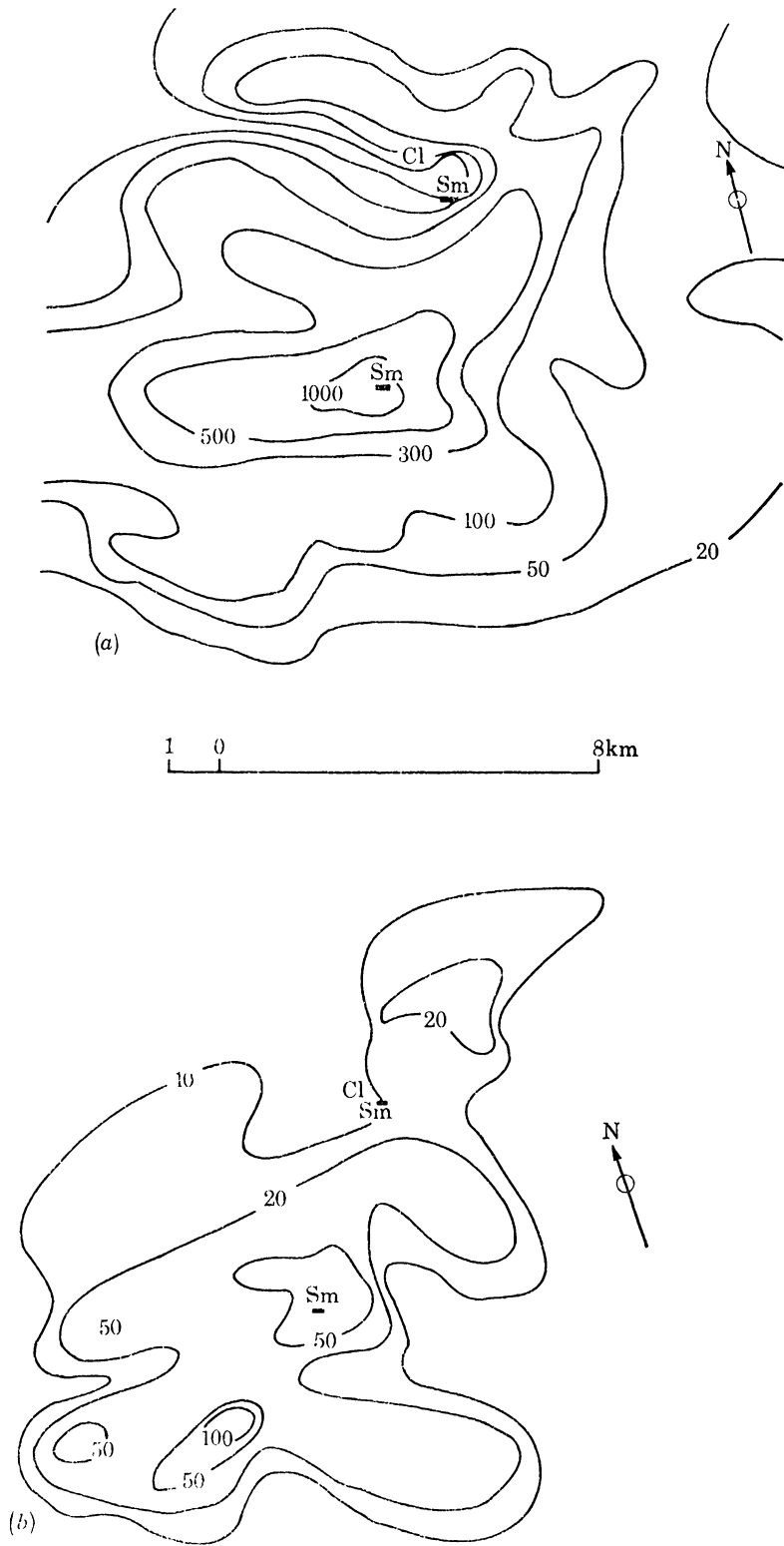
FIGURE 3. For legend see facing page.

criteria). This effect is usually manifest on organisms as: abnormal metabolism (e.g. accumulation of intermediate metabolites); abnormal physiological function (e.g. defective temperature- or water-regulation, nerve function); abnormal chromosomal behaviour, growth, embryonic development, tissue replacement or repair; impairment of sensory perception, behaviour, movement, reproductive capability; leading to characteristic disease symptoms and in severe cases to death. Experimental toxicity testing for various periods of exposure to the chemical, from hours to the whole life-cycle of the organism, will demonstrate which particular pattern of effects are to be expected and numerous examples appear in the literature.

TABLE 4. SUMMARY OF DOSE–RESPONSE SITUATION

dose	(1) 'level' in biosphere	determined by interactions between: (i) production (ii) transport and storage leakage (iii) use (iv) disposal methods (v) biogeochemical redistributions and degradations (see table 2)
	(2) trends in biosphere	determined by changes in relative activity of (i)–(v) above to give *rising* or *falling* trends
response	(3) effects of chemical	frequently no significant effect (passive chemicals); some chemicals have *beneficial* or *adverse* effects on biota (including man) and climate (active chemicals); potential adverse effects: (i) adverse effects on man from chemicals ingested via food, drinking water, respired air, drugs, contact (human health hazards) (ii) adverse effects on biota of air, water, soils (micro-organisms; wildlife; crops, livestock – loss of productivity) (iii) adverse effects on climate (CO_2, aerosols)
	(4) effects of rising trend of chemical	rise from 'natural' or 'background' level to *an effect level* where a *significant adverse response* is recognized in man or biota (from pre-set toxic level or percentage of affected organisms based on toxicological criteria)

Traditionally, toxicologists have been concerned with the harmful effects of one or several substantial doses of a chemical upon man, i.e. acute or subacute poisoning. The hazard from chemical disposal to the environment, however, is clearly one of virtually continuous exposure to minute amounts of a chemical over long periods of time, i.e. chronic affects. Latterly, toxicologists have turned their attention to this form of poisoning and what we know today about chronic effects on biota is very largely derived from chronic toxicological studies for man.

FIGURE 3. Local relative atmospheric burdens of lead, collected on moss-bags (Goodman & Roberts 1971) during one month's exposure around a smelting works (expressed as ng Pb cm^{-2} bag surface per day). (*a*) Works operational; (*b*) works not operational. (Data from G. T. Goodman, S. Smith & T. M. Roberts (1971, unpublished.) Sm, smelter processing ores containing lead; Cl Sm, metallurgical works not processing lead.

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This situation is particularly important in accumulative chemicals which over a long period of time can gradually build up in an organism to levels which may produce an irreversibly harmful effect. A good illustration is the way in which cadmium accumulates with age in the human kidney. If the 2 to 3 µg/day normally retained by the U.S. population without apparent harm were to increase to 5 to 6 µg/day, by middle-age the levels would be above renal zinc concentrations and this might result in kidney damage, proteinuria and hypertensive disease. Slow fluoride accumulation in livestock leading to the disease of fluorosis is an analogous case.

Usually, chronic effects are only apparent above a threshold concentration beyond which the severity is proportional to the amount finally retained. However, in some types of chemical, e.g. p-dimethylaminoazobenzene (butter yellow), the effect may be proportional to the total amount absorbed (not the amount finally retained). Other types of chemical, e.g. paraquat and dimethylnitrosamine, appear to trigger off an irreversible process following a single threshold dose leading to harmful effects long after the activating dose has disappeared – 'hit and run' poisons.

In most cases toxicity-testing procedures are adequate to reveal any potentially adverse effects, but should such an effect escape detection at this stage it may not be easy to recognize its occurrence in the field following release of the chemical on to the market. Four stages are then necessary:

(a) Recognition of the existence of an effect epidemiologically.

(b) Selection of a short-list of suspected causal agents.

(c) Demonstration of a correlation between one of the chemical agents and the effect.

(d) Proof of a causal connexion by experimental methods between the chemical agents and the effect.

Many effects are not specific to any one chemical substance, particularly those from low-dosage, long-term exposure (chronic effects). In wild species such effects, including mortality, will pass unnoticed, swamped by the natural variability in performance of an organism exhibited year by year from such natural causes as famines, cold spells, droughts, etc. A related problem is where rising levels of a chemical substance may raise the frequency of an existing disease which cannot be recognized as being on the increase because of sampling problems. For instance, a disease with an incidence of approximately 1 per 100000 per annum such as primary liver cancer in white man would need a sample of 6000000 individuals to validate statistically a doubling of its normal incidence (or 60000000 to validate a 25 % increase). Even a relatively frequent occurrence, e.g. crude death-rate at, say, 1 per 100 per annum in man, would require a sample size of 10000 to validate a 25 % increase.

Even if the effect is very striking and readily recognized epidemiologically as higher than average in certain localities, e.g. spina bifida or heart disease in man, it is difficult to select candidate causal agents.

Under field conditions it is often difficult, costly and time-consuming to demonstrate a correlation between a recognizable effect on man or biota and a suspected causal chemical agent. The result may also be very misleading unless followed by the experimental proof of a causal connexion between chemical and effect. We are frequently left with tantalizing situations, e.g. chemical analysis of 750 soils from gardens in North Wales, Cheshire and Devonshire, U.K., showed that the zinc/copper ratios were significantly higher in gardens of houses where a person had recently died of gastric cancer after ten or more years residence, as compared with houses where a person had died similarly but of a non-malignant cause (Stocks & Davies 1964). It will hardly be possible to formulate any reasonable hypothesis as to how zinc and copper may be directly or indirectly involved in neoplasm genesis without a good deal more experimental work. Again, the large-scale 'twenty-eight city study' in the U.S.A. (Carroll 1966) showed statistically significant correlations between atmospheric cadmium within the range 0.001 to 0.05 μg m^{-3} and heart disease, arteriosclerosis and hypertensive disease in their human populations. Such a correlation would have meant very little without the considerable experimental evidence of cadmium-induced hypertension in laboratory animals (see, for example, Schroeder & Vinton 1962; Schroeder, 1964, 1965; Schroeder, Kroll, Little & Livingstone, 1966; Schroeder *et al.* 1968).

Once a correlation has been established, the causal connexion between chemical and effect is often difficult to prove unequivocally, particularly in man. The difficulties arise because, by definition, it is never possible to *prove* that a substance has *no* effect, and furthermore, since it is unethical to use man intentionally as an experimental animal, cause–effect relations can only be observed from accidental, occupational or usage-exposure, in human beings, or by extrapolation from experimental animal results. Rigorous scientific proof is often unreasonably demanded in situations where enough is already known to justify the restriction or withdrawal of the suspect chemical as the most prudent course, pending further detailed investigation, e.g. infantile phocomelia following thalidomide (*N*-phthalyloyl-glutarimide) ingestion by the mother during the third to sixth week of pregnancy. In other instances, e.g. the withdrawal by certain countries of cyclamate sweeteners, over-reaction may have occurred on rather slender scientific evidence.

From time to time, many other chemical agents have been suspected of generating significant adverse effects in man, with varying degrees of proof – e.g. nitrite and nitrate generating nitrosamines; methyl mercury; polychlorinated biphenyls; nitrilo-triacetic acid; nitrogen trichloride acting on methionine; 2,4,5-trichloro-phenoxyacetic acid; monosodium glutamate; safrole (4-allyl-1,2-methylene-dioxybenzene).

Although frankly harmful effects can be made to occur in experimental animals and may even be seen in man under certain high-exposure régimes, the real problem is how often during the normal run of exposure does man or any other target species encounter these high dosages, i.e. although damage *can* occur, how often in actual practice *does* it occur? What consitutes a significant hazard for man is

a matter for a blend of scientific and social-value judgements. This demands a very wide-ranging appreciation of all the factors which contribute to the decision-making process and calls for a good deal of experience and common sense.

When such difficulties are encountered in recognizing potentially adverse situations for man – the most intensively studied of all species – it is no wonder that effects on inadequately known wild species in nature escape detection and ascription to a causal chemical agent.

In the past the first indications that a chemical substance in use was posing an environmental problem to wildlife were obtained from abnormally high mortality occurring in some noticed species. For instance, during and after 1956 increasingly large numbers of seed-eating birds were found dead in the spring in cereal-growing areas in the U.K. This stimulated intensive investigations which eventually implicated persistent organochlorine seed-dressings such as aldrin, dieldrin and heptachlor. It was decided that these species were sufficiently useful to man economically and as an amenity so that in 1961 there was a voluntary ban on dressing spring-sown cereals, under the 'Pesticides safety precautions scheme'. Similarly, extensive kills of fish in U.S. rivers during 1960–3 were traced to pesticides such as DDT.

Severe weather is often blamed for abnormal mortality. This can confuse the issue and delay the remedy. During the mid-1950s in Sweden, ornithologists noticed that the populations of several species of bunting, gallinaceous and predatory birds had decreased in number. It was not until 1964 that methyl mercury compounds in seed-dressings were officially recognized as the cause despite Borg's (1958) demonstration of very high levels of mercury in the birds found dead, particularly after spring and autumn sowing.

Our knowledge of wild species is so inadequate that it is rare to be able to spot an effect which in itself may be relatively harmless but which may act as an indicator of the trend towards harmful conditions. Eggshell thinning (Ratcliffe 1967), caused principally by DDE or other metabolites of DDT and to a smaller extent by polychlorinated biphenyls and cyclodiene insecticides, is one exception. From the late 1940s onwards, shell thinning has been identified in 9 wild-bird species out of 17 examined in the U.K. (Ratcliffe 1970) and 22 out of the 25 examined by Anderson & Hickey (1970) in the U.S.A. Several studies have been able to correlate DDE content of the eggs with percentage thinning (e.g. Blus *et al.* 1971; Blus, Gish, Belisle & Prouty 1972) and many experimental studies on bird species kept in captivity have induced eggshell thinning by dietary doses of those organochlorines (Heath, Spann & Kreitzer, 1969; Porter & Wiemeyer 1969; Bitman, Cecil, Harris & Fries, 1969; Longcore, Samson & Whittendale 1971). Such thinning in nature was frequently associated with dead embryos and parental egg-smashing, and in North America has been associated with population decreases in certain bird species but not others (summarized by Henny (1972) and Stickel (1973)). In Britain, however, shell thinning is not thought to be responsible for population decreases observed in certain British raptorial species (Cooke 1973).

The importance of the shell thinning phenomenon is that it provides a useful quantitative tool for monitoring the environmental effects of organochlorines. Thus, evidence that a significant thinning is starting to occur will indicate the prevailing level of organochlorines in an area so that a prediction can be made about the likely future effects of a steady build-up on the bird species involved as well as for associated wildlife or resource species.

7. PERCEIVING AND PREDICTING CHEMICAL EFFECTS

The question of exactly what constitutes an environmental problem and how seriously it is perceived as a problem by the public or by government and environmental scientists has received little attention. Very often potential chemical problems are evaluated less on human health grounds than on nuisance or amenity grounds and it is important to clarify the psycho-social, cultural and economic factors upon which perception is based.

Many scientists have criticized the forecasting of possible harmful events before they appear as unduly alarming to the public. The matter largely depends on whether the responsible environmental authorities have a past record of being suddenly confronted with unplanned environmental problems for which no contingency plans have been made.

The hurried attempts to counteract unforeseen side-effects of chemical action as they appear in the environment inevitably creates a feeling of insecurity because the public always wonders what other incipient problems as yet undetected may be growing to a point of producing overtly harmful effects. Forecasting likely problems well before they occur allows for time to react in a more judicious way should the problem finally arise and restores the public feeling of being in control, i.e. public nervousness about potential chemical hazards is probably more a function of the past record of the responsible authorities in controlling previous chemical events rather than of the publicity given to future problems.

The view has often been expressed that anxiety over chemical substances in the environment during the twentieth century is proportional to the analytical chemist's ability to detect, and hence discover or predict, smaller and smaller quantities of a chemical. Analysis to the picogram level is now a commonplace, so that nowadays potentially harmful chemicals appear to be ubiquitous over the globe. But this is to confuse *levels* of a chemical, which do not really matter, with the *effects* produced by it on organisms or climate, which may well be very important.

Attention has already been drawn (§ 6*a*) to the need for dynamic models to predict the flow and partitioning of a substance in the biosphere at known rates of injection and decay. Although this capability may be some way off realization, a more empirical approach making use of geographical discontinuities in chemical usage has some value. It is frequently possible to analyse for prevailing levels of a chemical substance and search for likely effects under conditions of: (*a*) very

high exposure (e.g. human occupational exposure); (*b*) specially high exposure (e.g. human and biotic populations living close to works where a chemical is made or processed); (*c*) high exposure (e.g. intensively urban–industrial or agricultural environments); (*d*) medium exposure (e.g. rural parts of densely populated urbanized countries); (*e*) low exposure (e.g. remote regions of the world where the inhabitants practise hunting, pastoralism or primitive agriculture). This process of moving spatially from the 'hot spot', where the most overt effects of a chemical can be most easily recognized, to the 'baseline' situation in remote regions is a parallel of the build-up with time of a chemical substance. This approach, together with the analysis of recent historical trends in a chemical from the examination of sediments, ice-cores, peat deposits, tree rings, coral-growths, feathers, etc., help to recognize, interpret and predict likely future secular trends.

Such data requires a great deal of time and effort to collect and it is obviously only practicable to do so for chemical substances of proven environmental importance, e.g. Pb, Cd, Hg, ΣDDT and certain other organochlorines, PCB, petroleum oils, and relevant compounds in the cycles of S, N and C.

When a first approximation to screening for substances of likely importance is required it is necessary to fall back on criteria such as those tentatively suggested in table 1 and on chemical structure. Experience has shown that when attempting to predict likely harmful effects to wildlife, criterion 4 – environmental persistence – is probably the most important. This is because there is usually some wild species or other to which the substance is toxic even if it is not shown to be toxic in laboratory or field trials on a limited range of test species. Provided the chemical can persist in the environment, the normal biogeochemical cycles will in time deliver it to the unknown sensitive species. Thus, from the point of view of wildlife, all chemical substances should ideally either be passive or, if active, have a half-life in the environment of less than a week. The considerable knowledge of chemical-bond energies obtained from a study of thermodynamics should easily make it possible to design chemicals of this nature. Thus, organophosphorus pesticides, although extremely toxic (oral LD_{50} 3 to 6 mg/kg for parathion, Ben-Dyke, Sanderson & Noakes 1970), never move far from their site of application, being destroyed in a few days. Relatively speaking, they do not constitute an environmental hazard.
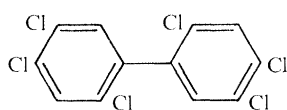
a typical PCB
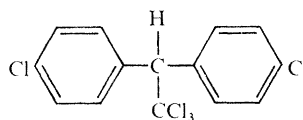
p,p′-DDT
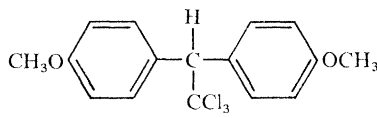
methoxychlor
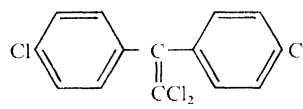
p,p′-DDE

Although a great deal is known about the effect of molecular architecture upon the ability of the human body to detoxify a drug, much less is known about the relationship of molecular structure to environmental persistence.

The four substances shown on p. 146 have rather similar molecular structures. However, PCB is very persistent, whereas methoxychlor is rapidly broken down so is rarely found in tissues of warm-blooded animals. By contrast, DDT is relatively long-lived (average soil persistence 4 to 30 years for 95 % disappearance, Edwards 1965) and DDE even more so. Toxicities also differ; PCB and DDE have somewhat similar toxicities, with DDT about ten times more potent than PCB, and methoxychlor about the same or even more toxic than DDT.

It seems clear that the systematic collection and classification of as wide a range of physicochemical and biological properties as possible for each chemical substance will build up a picture of its environmental behaviour. There is no simple means of arriving at an estimate of potential hazard.

Bearing this in mind, it is probably more prudent to introduce a new chemical gradually into the environment by a regulated system of provisional licensing and restricted usage which can be gradually relaxed as the chemical is seen to be without inconvenient side-effects. Such a system is more reasonable than rather liberalized initial usage followed by banning if difficulties arise and has been followed by certain countries with success for many years.

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